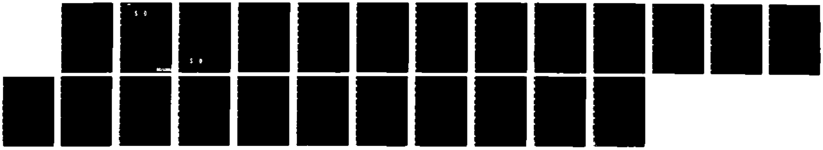
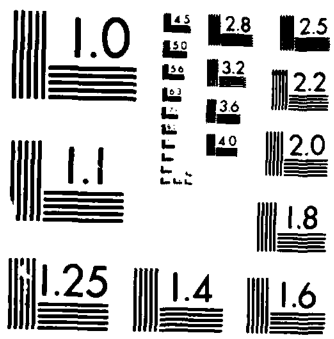
AD-A171 944 INTERPLANETARY DUST AND THE VISIBLE/INFRARED SKY BACKGROUND RADIATION(U) FLORIDA UNIV GAINESVILLE SPACE ASTRONOMY LAB J L WEINBERG 07 JUL 86 AFOSR-TR-86-0687 1/1

UNCLASSIFIED AFORR-83-0107 F/G 3/1 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963

6a. NAME OF PERFORMING ORGANIZATION
University of Florida

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
Air Force Office of Scientific Research

6c. ADDRESS *(City, State and ZIP Code)*
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8a. NAME OF FUNDING/SPONSORING ORGANIZATION
Air Force Office of Scientific Research

8b. OFFICE SYMBOL *(If applicable)*
AFOSR / NP

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-83-0107

8c. ADDRESS *(City, State and ZIP Code)*
Building 410
Bolling Air Force Base, DC 20332

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61102F	2311	A1	N/A

11. TITLE *(Include Security Classification)* Interplanetary Dust and the Visible/Infrared Sky Background Radiation

12. PERSONAL AUTHOR(S)
Weinberg, Jerry L.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Yr., Mo., Day)*	15. PAGE COUNT
Final	FROM 830401 TO 840930	860707	19

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
interplanetary dust; zodiacal light; sky background; infrared

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A multidisciplinary approach is developed to provide information on the optical and physical properties of interplanetary dust, its location in space, its origin and dynamics, and its contribution to the astronomical background radiation in the infrared. This approach makes use of ground-based, Earth-orbital, and deep-space probe observations of zodiacal light; development and use of inversion techniques to derive information on particle properties and distribution from zodiacal light observations; analysis of comet tail observations; theoretical calculations and laboratory measurements of scattering by spheroids, cylinders and irregular particles; studies of interplanetary dust dynamics. Results are presented for the 18-month period starting 1 April 1983.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER *(Include Area Code)*	22c. OFFICE SYMBOL
Henry R. Radoski	202/767-4906	NP

AFOSR-TR- 86-0687

FINAL SCIENTIFIC REPORT

Interplanetary Dust and the Visible/Infrared
Sky Background Radiation

U.S. Air Force Office of Scientific Research
Grant AFOSR-83-0107
to University of Florida

1 April 1983 - 30 September 1984

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7 July 1986

Final Scientific Report
AFOSR Grant 83-0107
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Sky Background Radiation

7 July 1986

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Grant AFOSR-83-0107
Interplanetary Dust and the Visible/Infrared Sky Background Radiation

Background Information

There is only one source of information on the integrated properties of the "steady state" small particle ensemble of interplanetary objects: the zodiacal light. Although brightest in the zodiacal band (hence, its name), the zodiacal light extends over the entire sky and is caused by sunlight scattered and absorbed by interplanetary grains. Observations of brightness, polarization, and color of the scattered radiation and of the thermal emission contain information on size, shape, composition, and overall properties of the grains. Optical observations made from different locations in the solar system and infrared observations at different wavelengths from any location give the change in zodiacal light with heliocentric distance. These data are needed to determine the spatial distribution of the dust and changes in its optical properties as function of sun-particle distance and height above or below the plane(s) of maximum concentration.

In terms of the scattering or photometric characteristics, the zodiacal light cannot be seen "by itself" except close to the sun where it is very bright compared to the background starlight. At visual wavelengths in and near the galactic plane the background starlight dominates, whether observed from space or from the ground. For ground observations near the horizon, airglow line emissions - and in some wavelength regions even airglow continuum emission - dominate. Infrared observations from the ground are generally limited to "dry" sites and to selected infrared windows (spectral regions where infrared transparency of the atmosphere is high).

Zodiacal light was expected to be the limiting factor for astronomical observations from 1-20μm (Report of the Joint U.S., Netherlands, and U.K. Scientific Working Group on the IR Astronomy Satellite - IRAS, and IR observations such as those of Price, et al., Astron. J., 85, 765, 1980). This was confirmed by the recent IRAS observations (see the various results reported in Ap. J. Letters, 278, March 1, 1984 and Science, 224, April 6, 1984).

The IR output of the interplanetary zodiacal dust cloud can only be understood in the full context of the physics of light scattering. Sunlight warms the circumsolar dust to room temperature (near the Earth), causing it to emit IR radiation. The rate of particle heating is determined by the particle's ability to absorb the visual radiation supplied by the sun. The heating process is a function of particle size, shape, visual index of refraction and its heliocentric distance - properties which can only be inferred from laboratory studies, theory, and multicolor observations from 1 AU and from a deep-space probe. Some of these data exist, but, historically, more time and effort have been devoted to morphological studies of the zodiacal light than to analysis in terms of the scattering and absorption of sunlight by interplanetary dust grains...and there are still large gaps even in the morphology:

- angular extent (most observations have been made in or near the ecliptic)
- color (observations have generally been made in one or two "nearby" wavelengths, $1/\lambda$ not very different)
- resolution in sky coverage is limited.

In addition, polarization and spectroscopic observations are relatively rare, and data for near sun (closer than 30°) regions are especially lacking.

Space Astronomy Laboratory staff have studied the diffuse astronomical background radiation for over 25 years, with emphasis on increasing observational accuracy and sky and wavelength coverage and on deconvolving the zodiacal light to provide information on the interplanetary dust. This report covers 18 months (April 1983 through September 1984) of a continuing long-term study of interplanetary dust and the visible/infrared sky background radiation.

Overall Program Objectives and Strategy

A multidisciplinary approach is developed to provide information on the optical and physical properties of interplanetary dust, its location in space, its origin and dynamics, and its contribution to the astronomical background radiation in the infrared. This approach makes use of a large library of observational data on the brightness, polarization, and color (near UV to near IR) of the zodiacal light, including: extensive ground-based observations of

the light of the night sky from Mt. Haleakala, Hawaii, the first observations of the change in zodiacal light with heliocentric distance (Pioneer 10 and 11 deep-space probes), the first multicolor observations of large regions of the sky from space (Skylab), and additional sky and wavelength coverage from Shuttle mission 3 (March 1982). We have reduced and analyzed some of the Pioneer 10 and Skylab data and combined these data with ground-based results to map zodiacal light brightness, polarization, and color over selected regions of the sky as a function of heliocentric distance. These optical (scattering) data contain unique information on the nature and distribution of these interplanetary grains. Parallel studies have been made of the dynamics of small particles in the solar system; of the scattering properties of various particle sizes, shapes, compositions, and spatial distributions [the Space Astronomy Laboratory has a long-term, ARO/AFOSR - supported program of theoretical studies and microwave analog scattering measurements to determine the scattering by irregularly shaped particles]; and of methods for inverting the zodiacal light brightness integrals (scattering and emission) to derive information on the spatial distribution and properties of the grains.

Our ultimate goal is to characterize the interplanetary dust complex via its visible and IR sky background radiation - especially, to evaluate and understand existing IR observations of zodiacal emission and to predict brightness, color, angular distribution, spectral signatures, and structure in observations not yet available.

Summary of Results (After 18 months)

- The Mt. Haleakala, Hawaii night sky observing facility and photopolarimeter were reactivated and used in an observational search for the Schuerman Dust Arcs. Observing conditions, celestial aspect, and limited resources resulted in inadequate data; the search should be repeated.
- A comparison of laboratory microwave scattering data and photopolarimetry of the tail of Comet Ikeya-Seki (1965 VIII) suggests that only a relatively small set of particle material/shape parameters could account for the observed cometary polarization.

- Studies of interplanetary dust dynamics included the effects of perturbations by the inner planets and the gravitational zone of influence of a planet acting on small celestial bodies.
- A new analytical inversion formalism (Henyey - Greenstein) was developed for use with the zodiacal light brightness integral to derive the volume scattering phase function of interplanetary dust.
- Pioneer 10 and ground-based observations of zodiacal light brightness were found to have small scale structures, with the former structures reproducing at the same elongations above and below the ecliptic and at different heliocentric distances.
- A relatively high resolution observational model of the zodiacal light at 5080A was prepared for elongations 30° to 56° and ecliptic latitutdes -30° to 30°.
- Pioneer 10 observations of zodiacal light seen from beyond the Earth (between 1 and 3 AU) were used to depict changes in the topology (shape) of the zodiacal light with sun-spacecraft distance and with angular distance from the sun. Comparisons were made with the corresponding views from the Earth and from the Helios 1 and 2 spacecraft.

These results are described in detail in grant-related publications (see list which follows and the attached copies of the first page of each of these publications).

Grant-Related Publications[i]

Giovane, F., Weinberg, J.L., Mann, H.M., and Oliver, J.P. 1985. An Observational Search for the Schuerman Dust Arcs, in Proc. IAU Colloq. 85, Properties and Interactions of Interplanetary Dust, R.H. Giese and P. Lamy (eds.), D. Reidel Publ. Co. (hereafter IAU 85), 39-42.

Gustafson, B.A.S. 1985. Laboratory Results on Polarization Properties of Elongated Particles and Comparisons to Dust in the Tail of Comet Ikeya-Seki (1965 VIII), IAU 85, 227-230.

Gustafson, B.A.S. 1985. A New Approach to Evaluate Planetary Perturbations on a Cloud of Dust in Low Eccentricity Heliocentric Orbits, IAU 85, 381-384.

Gustafson, B.A.S., 1985. Planetary Perturbations: Effects on the Shape of a Cloud of Dust in Circular Heliocentric Orbits, IAU 85, 385-388.

Gustafson, B.A.S. and Misconi, N.Y. 1983. Can Cometary Dust Perturbed by the Inner Planets be an Explanation for the Observed Distribution of Interplanetary Dust?, in Proc. Int'l. Conf. on Cometary Exploration, Vol. 2, 121-133.

Gustafson, B.A.S. and Misconi, N.Y. 1985. Interplanetary Dust Dynamics I. Long-Term Gravitational Effects of the Inner Planets on Zodiacal Dust, Icarus, 64, 3484-3491.

Hong, S.S. 1984. Henyey-Greenstein Representation of the Mean Volume Scattering Phase Function for Zodiacal Dust, Astron. Astrophys., 146, 67-75.

Hong, S.S. 1985. A Method for Deriving the Mean Volume Scattering Phase Function for Zodiacal Dust, IAU 85, 215-218.

Hong, S.S., Misconi, N.Y., van Dijk, M.H.H., Weinberg, J.L., and Toller, G.N. 1985. A Search for Small Scale Structures in the Zodiacal Light, IAU 85, 33-37.

Misconi, N.Y. and Rusk, E.T. 1985. The Size of the Gravitational Zone of Influence of a Planet Acting on the Orbital Elements of Small Celestial Bodies, Planetary Space Sci., 33, 1359-1362.

Misconi, N.Y. and Rusk, E.T. 1985. The Gravitational Zones of Influence of the Planets Acting on Small Celestial Bodies, IAU 85, 377-380.

Misconi, N.Y. and Weinberg, J.L. 1985. Ground-Based Observations of Near Ecliptic Zodiacal Light Brightness, IAU 85, 11-15.

Toller, G.N. and Weinberg, J.L. 1985. The Change in Near-Ecliptic Zodiacal Light Brightness with Heliocentric Distance, IAU 85, 21-25.

Weinberg, J.L. 1985. Zodiacal Light and Interplanetary Dust, IAU 85, 1-6.

[i]The first page of each publication is attached.

AN OBSERVATIONAL SEARCH FOR THE SCHUERMAN DUST ARCS

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ABSTRACT. Large-scale interplanetary dust arcs were predicted by Schuerman (1980) to be associated with the planets. An arc, if one exists, would produce asymmetries on opposite sides of the Gegenschein during the Earth's two passages through the arc each year. A brief description is given of Gegenschein/arc observing constraints, of future viewing opportunities, and of the results of a test program conducted from Mt. Haleakala, Hawaii, in Jan/Feb 1984 when the Earth encountered the arc associated with Saturn.

In the course of performing dust dynamics studies associated with the International Solar Polar Mission (ISPM) Zodiacal Light Experiment (Schwehm, et al., 1981) and with analysis of Pioneer 10/11 data, Schuerman (1980) found that a previously unsuspected solar-system phenomenon might exist: interplanetary dust arcs which could span the entire solar system. An arc, hereafter called Schuerman Dust Arc or SDA, was predicted to be associated with each planet - those of Jupiter and Saturn being predominant. His prediction was based on the results of recalculating the restricted three-body problem to include radiation pressure. The combined effects of sunlight and gravity extend the classical equilibrium (Lagrangian) points L_4 and L_5 into a circular arc extending from L_4 through the sun to L_5 - an arc made up of "trapped" .01 μm to 1.0 μm size particles. For particles in this size range, the radiation pressure force is not negligible compared to the gravitational force. Such grains are referred to as β particles. Perturbing and/or destructive forces such as the Lorentz force resulting from the interplanetary magnetic field, solar wind interaction, and gravitational effects of other planets were not included in Schuerman's treatment. Thus, the stability of the arcs has not been definitively established. Schuerman estimated that for a typical value of $\beta = 0.57$, particles in the Jupiter-sun and Saturn-sun arc systems have characteristic lifetimes T of 14,700 and 50,000 years, respectively. Since β particles now exist in the interplanetary medium and the gradual spiraling into the sun due to the Poynting-Robertson effect occurs on a time scale on the order of T, then the replenishment mechanism, regardless of details as to its source, must be of sufficiently short time scale to replenish the interplanetary

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 39–42.

LABORATORY RESULTS ON POLARIZATION PROPERTIES OF ELONGATED PARTICLES AND COMPARISONS TO DUST IN THE TAIL OF COMET IKEYA-SEKI (1965 VIII)

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ABSTRACT. Data obtained through microwave analog measurements are used to compare optical polarization characteristics of silicate particles ranging in shape from spheroids and cylinders to chains of spheres. It is confirmed that the dependence of the degree of polarization on scattering angle is a powerful indicator of particle shape. The reversal and steep gradient in the degree of polarization found by Weinberg and Beeson (1976a,b) in the dust tail of comet Ikeya-Seki (1965 VIII) is suggestive of laboratory measurements corresponding to 1.6 μm long, 0.4 μm in diameter silicate cylinders.

1. INTRODUCTION

Krishna Swamy (1978) showed that the run of the degree of polarization with scattering angle observed in the tail of comet Ikeya-Seki (1965 VIII) could result from size segregation among spherical particles. Segregation along the tail is expected due to faster diffusion away from the tail for low mass particles. But spherical particles are probably rare in a disintegration event. Cubes or other rough shapes may be a better approximation. Sekanina and Farrell (1980) found independent evidence for elongated grains in the tail of comet West (1976 VI), and suggested that chain like aggregates may have been common. Schuerman et al. (1981) and Zerull (1985) concluded that there are marked deviations from Mie polarization patterns for the case of non-spheres. The degrees of polarization produced by chains of five spheres, similar sized circular cylinders and spheroids are compared to illustrate the effect of detailed shape including sharp edges. In this paper, we concentrate on the degree of polarization. This quantity, a ratio of intensities, is independent of the (unknown) number of particles along the line of sight. In addition, the angular dependence of the degree of polarization is found to be a powerful indicator of particle parameters (see also Schuerman et al., 1981 and Zerull, 1985).

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 227–230.

A NEW APPROACH TO EVALUATE PLANETARY PERTURBATIONS ON A CLOUD OF DUST IN LOW ECCENTRICITY HELIOCENTRIC ORBITS

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ABSTRACT. Dynamical perturbations on *ensembles* of particles in heliocentric orbits of low eccentricity are integrated over time. The dust is perturbed by radiation pressure, Poynting-Robertson drag, their corpuscular counterparts, and by gravitation due to any number of planets. A dust cloud is represented by a set of centroids and orbital dispersions (about the centroids). Gravitational perturbations on the centroid are derived from a single matrix, valid for any planet, in the appropriate frame of reference. After transformation of the time derivatives to a common coordinate system, the perturbation rates are summed up and integrated. The time dependence of the planets' orbital elements are evaluated inside the time integral.

1. INTRODUCTION

It is time-consuming and costly to estimate overall perturbations on a dust cloud by computing trajectories of individual dust particles. The efficiency is increased through the use of centroids to represent sets of orbits. Perturbations due to each planet are computed separately. Geometries are chosen such that the planet's perturbations on a centroid may be expressed by a *single quantity* depending only on the angle that the plane containing the centroid makes to the planet's orbital plane and the ratio of heliocentric distances. A comparatively simple interpolation-formula allows the matrix representing the perturbations to be stored on-line. Properly scaled, a single matrix may represent perturbations by any planet in the appropriate geometry.

2. COMPUTATIONAL PROCEDURE

2.1 The approach

Perturbations on *ensembles* of particles are evaluated as shown in the flow diagram, Figure 1. The ensemble is divided into a set of fictitious orbits, each a centroid for a set of dust trajectories. Each

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 381–384.

PLANETARY PERTURBATIONS: EFFECTS ON THE SHAPE OF A CLOUD OF DUST IN CIRCULAR HELIOCENTRIC ORBITS

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ABSTRACT. Synthetic infrared pictures are used to illustrate changes in the shape of portions of an interplanetary dust-cloud. The dust particles, in circular heliocentric orbits, are perturbed by radiation and corpuscular forces combined with gravitational disturbances by the major planets. Dust in the inner solar system and close to the ecliptic or the orbital plane of Venus is brought to a more narrow range of ecliptic latitudes. A dust-band evolves near and inside the orbit of Venus. The cloud's shape is less affected at high ecliptic latitudes.

1. INTRODUCTION

Derivations of the shape of the zodiacal cloud based on dynamical evolution are initial-value problems. Because the source remains unknown as well as the cloud's long-term steady state or transient nature, no statements can be made regarding the absolute shape of the interplanetary dust cloud. Instead, we address the problem of *changes* in the shape of a *portion* of the cloud as the dust spirals through the inner solar system. Conventional wisdom states that dust migrates through the solar system while losing angular momentum to drag forces. It is not yet established whether transfer of momentum from the planets may affect the rate significantly. The resulting uncertainty in magnitude of the perturbations has little effect on our qualitative results. Because orbital eccentricities are neglected, momentum transfer and, by implication, dynamical life-times of the dust are not addressed in this paper.

2. OBSERVATIONS

Observations show that the symmetry plane of the inner zodiacal cloud is close to the orbital plane of Venus (Misconi, 1980, and references therein). Leinert *et al.* (1980) concluded that this symmetry extends to 1 A.U., whereas most observations in this region favor a plane close to the invariable plane of the solar system (Misconi, 1980). The brightness plane of symmetry is close to the plane of maximum particle number densities except where shifted by the dust particles' light scattering characteristics, as in the Gegenschein (Misconi, 1981).

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 385–388.

CAN COMETARY DUST PERTURBED BY THE INNER PLANETS BE AN EXPLANATION FOR THE OBSERVED DISTRIBUTION OF INTERPLANETARY DUST?

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ABSTRACT

Numerical integrations of perturbation equations using the Encke method show that the long-term dynamical evolution of interplanetary dust is strongly affected by the inner planets. Perturbations in inclination and ascending node may explain the observed inclination of the plane of maximum dust density. Non monotonic changes are found in the semi-major axes and eccentricity. As a result, temporal increases in semi-major axis may slow the sink of zodiacal dust into the sun with respect to current estimates.

INTRODUCTION

Recent studies have shown that the plane of maximum dust density (symmetry plane) of the zodiacal cloud varies in inclination with respect to the ecliptic plane as a function of heliocentric distance (Misconi and Weinberg, 1978; Misconi, 1979; Leinert, et al., 1980). This suggests that we are dealing with a multiplicity of symmetry "planes" which tend towards the orbital planes of the planets (Fig. 1). Consequently, the suggestion was made that long-term gravitational perturbations by Jupiter and the inner planets are influencing the spatial density distribution of interplanetary dust (Misconi, 1977; Misconi and Weinberg, 1978).

Long-term gravitational perturbations by the inner planets on the orbital elements of the dust have not previously been investigated. Studies on the gravitational effect of Jupiter (Brouwer and Clemence, 1961; and Smith, 1964) led to the belief that Jupiter is the sole perturber of the dust and that the symmetry plane of interplanetary dust is expected to be near the invariable plane of the solar system which, in turn, is near the orbital plane of Jupiter. Since that belief is not supported by observations, the

Interplanetary Dust Dynamics

I. Long-Term Gravitational Effects of the Inner Planets on Zodiacal Dust

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Received March 22, 1985; revised April 23, 1985

Whereas the inner planets' perturbations on meteoroids' and larger interplanetary bodies' orbits have been studied extensively, they are usually neglected in studies of the dynamics of smaller particles producing the zodiacal light through scattering of sunlight. Forces acting on these dust particles are fairly well known and include radiation forces and interaction with the solar wind. This article is the first in a series aimed at improving our knowledge of the dynamical evolution of dust in interplanetary space by studying the *combined* effects of these perturbations including gravitational perturbations by the planets Venus, Earth, Mars, and Jupiter. The necessity of including effects of the inner planets in dust dynamics investigations is established. Sample trajectories are presented to illustrate commonly occurring phenomenae, such as nonmonotonic changes in semimajor axis, eccentricity, inclination, and in the line of nodes. These perturbations are shown to be due to the inner planets as opposed to Jupiter or nongravitational forces.

Studies of the zodiacal light in the last decade have supplied the first detailed information on the large-scale properties of the interplanetary dust complex, and are suggestive of planetary influences. We adopt common practice and refer to particles with radii less than 100 μm as dust. This is convenient because the large-scale distribution of this size particles can be studied from observations of the zodiacal light, which is produced through scattering of sunlight by primarily 10- to 100-μm-size dust (Giese and Grün, 1976; Röser and Staude, 1978). The spatial density distribution and other properties of the dust cloud were determined from measurements by optical, impact, and other dust detection instruments on board the Pioneer 10 and 11, and the Helios A and B space probes (Weinberg and Sparrow, 1978). The plane of maximum dust density (symmetry plane) of the zodiacal cloud was found to vary in inclination with respect to the ecliptic plane as a function of heliocentric distance (Misconi and Weinberg, 1978; Misconi, 1979; Leinert *et al.*, 1980). This suggests that we are dealing with a multiplicity of symmetry "planes" which tend toward the orbital planes of the planets (Fig. 1). Consequently, the suggestion was made that long-term gravitational perturbations by Jupiter and the inner planets are influencing the spatial density distribution of interplanetary dust (Misconi, 1977; Misconi and Weinberg, 1978). Morfill and Grün (1979) have suggested that the Lorentz force resulting from the interaction of the dust with the interplanetary magnetic field is influencing the dust density distribution. This influence would give a symmetry toward the solar equatorial plane. One difficulty with Morfill and Grün's suggestion is that the Lorentz force becomes negligible for large particles (> 10 μm) from which most of the zodiacal light is now thought to arise. Additional difficulties arise from uncertainties in the value for the charge of these particles and in the nature and behavior of the interplanetary magnetic field through lifetimes of the particles of the order of 10^4–10^5 years. Finally, if the Lorentz force is responsible for the observed symmetry plane, then one would expect the plane to have a smooth decrease in inclination away from

0019-1035/85 $3.00

Astron. Astrophys. 146, 67–75 (1985)

ASTRONOMY
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Henyey-Greenstein representation of the mean volume scattering phase function for zodiacal dust

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Received July 9; accepted December 14, 1984

Summary. To determine the scattering characteristics of interplanetary particles, we substitute a linear combination of three Henyey-Greenstein functions for the mean volume scattering phase function in the zodiacal light brightness integral. Residuals are obtained by comparing the observed zodiacal light in the ecliptic with results of the integral. Minimization of the residuals leads to a scattering function which has a strong peak in the forward direction, an isotropic part at intermediate scattering angles and a mild enhancement in the backward direction.

The same method is employed to analyze the polarized components of the zodiacal light. The scattering phase function, $\Phi_\perp(\Theta)$, for the component polarized perpendicularly to the scattering plane remains substantially higher than the parallel component, $\Phi_\parallel(\Theta)$, over most scattering angles. But at scattering angles greater than $\Theta \simeq 165°$, $\Phi_\perp(\Theta)$ becomes less than $\Phi_\parallel(\Theta)$ with a maximum difference between the two occurring at $\Theta \simeq 175°$.

Key words: zodiacal light – scattering phase function – interplanetary dust

1. Introduction

Understanding how interplanetary dust particles scatter sunlight into different directions is one of the prime objectives in zodiacal light studies (see reviews by Leinert, 1975; Weinberg and Sparrow, 1978). Such scattering characteristics give important clues for the chemical and physical identities of the interplanetary particles (Giese et al., 1978; Greenberg and Gustafson, 1981; Weiss-Wrana, 1983), and also provide an essential stepping-stone for determining the morphology of the zodiacal dust cloud (Dumont, 1976a; Leinert et al., 1976; Buitrago et al., 1981, 1983). During the last decade serious attempts have been made to determine the scattering phase function for interplanetary particles from the observed brightness of zodiacal light (Dumont, 1974, 1976a; Dumont and Sánchez, 1975b; Leinert et al., 1976). Two principal assumptions employed in these attempts are as follows: (i) Scattering properties of interplanetary particles are independent of location within the zodiacal dust cloud. (ii) Dust distribution in the ecliptic plane follows a simple power-law relation with heliocentric distance. There are indications that these assumptions are unwarranted (Schuerman, 1980; Hanner et al., 1976); nevertheless, they are necessary simplifications taken in order to make the problem manageable. Thus, we should view the resulting empirical scattering phase function only as an average over rather imprecisely defined parameters.

Most theoretical methods for deriving the empirical scattering phase function require taking derivatives of the observed zodiacal light brightness. As an alternative, we take an integral approach to the problem. We utilize the versatile Henyey-Greenstein function which conveys essential characteristics of a complex scattering pattern by varying a single parameter. Substituting a linear combination of Henyey-Greenstein functions for the scattering phase function in the zodiacal light brightness integral, we form residuals between results of the brightness integral and the observed brightness. The residuals are then minimized by the method of non-linear least squares to determine the best combination of parameters for the scattering phase function of the interplanetary particles.

In the second section we present basic formulations for deriving an empirical scattering function, emphasizing the difference between differential methods of inversion and our method of non-linear least squares. In the third section the observed total brightness of the zodiacal light in the ecliptic is analyzed to show advantages as well as limitations of the integral method. In the fourth section the polarized brightness of the zodiacal light is analyzed to determine polarization characteristics of the interplanetary particles. The paper concludes with discussions on future improvements.

2. Inversion of the brightness integral

2.1. Zodiacal light brightness integral

The surface brightness of zodiacal light $Z(\varepsilon)$ seen in the ecliptic at solar elongation angle ε is the sum of scattered sunlight received from all the particles along the given direction; hence, $Z(\varepsilon)$ is given by

$$Z(\varepsilon) = \int_0^\infty \int_0^\infty F(r)n(r)f(s)\sigma(s)\phi(\Theta; s)\,ds\,dl, \tag{1}$$

where variables r, dl, and Θ represent, as schematically illustrated in Fig. 1, the heliocentric distance, line-element, and scattering angle, respectively, and s is particle radius. The solar flux at heliocentric distance r is denoted by $F(r)$, which can be replaced by an inverse-square relation $F_0(r_0/r)^2$ with F_0 being the solar flux at heliocentric distance r_0. Note that this formulation assumes the particle scattering properties to be independent of location. With

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A METHOD FOR DERIVING THE MEAN VOLUME SCATTERING PHASE FUNCTION FOR ZODIACAL DUST

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ABSTRACT. A linear combination of 3 Henyey-Greenstein phase functions is substituted for the mean volume scattering phase function in the zodiacal light brightness integral. Results of the integral are then compared with the observed brightness to form residuals. Minimization of the residuals provides us with the best combination of Henyey-Greenstein functions for the scattering phase function of zodiacal dust particles.

1. INTRODUCTION

Most theoretical methods for deriving an empirical scattering function for interplanetary dust particles require taking derivatives of the observed zodiacal light brightness. Observational errors are easily amplified in the process of differentiation and likely to distort the scattering function derived therefrom. As an alternative, we take an integral approach: A utilization of the versatile Henyey-Greenstein (HG) function as a parameterized trial scattering function will enable us to employ the method of non-linear least squares in determining the mean volume scattering phase function for zodiacal dust particles.

2. BRIGHTNESS INTEGRAL WITH THE HENYEY-GREENSTEIN FUNCTION

A linear combination of three HG functions

$$\phi\,(\theta;\, g_k, w_k\,) = \sum_{k=1}^{3} \frac{w_k}{4\pi} \frac{(1 - g_k^2)}{(1 + g_k^2 - 2g_k \cos\,\theta\,)^{3/2}} \qquad (1)$$

having different asymmetry factors, g_k, adequately describes such general features as the forward peak, isotropic middle, and backward enhancement in a particle scattering pattern. Here, w_k represents relative weights of the three components, and θ denotes scattering angle. With the usual power-law relation, $n(r) = n_o(r_o/r)^{\nu}$, for the heliocentric density distribution of particles, the zodiacal light

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A SEARCH FOR SMALL SCALE STRUCTURES IN THE ZODIACAL LIGHT

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ABSTRACT. Gegenschein observations from Pioneer 10 were found to have brightness structures with an amplitude of about 10% and a period of several to ten degrees in elongation. A search is made for such structures in high angular resolution ground-based observations from Mt. Haleakala, Hawaii. A new empirical method is used to correct for atmosphere-originated radiation. Background starlight is subtracted using Pioneer 10 observations from beyond the asteroid belt. Preliminary analysis of the ground data also indicates the presence of small amplitude structures in the brightness distribution.

This is a first report on our search for small scale structures in the zodiacal light brightness. By structures we mean small amplitude spatial fluctuations in the brightness distribution. Such structures might be expected from inhomogeneities in the spatial distribution of the zodiacal dust and/or structure in the scattering phase function. There have been a number of observational hints for the existence of such structures. Ground-based observations of zodiacal light brightness by Weinberg (1963) show an enhancement at elongation 135°, which also has a counterpart in the polarized brightness (Weinberg, 1964; Frey, et al., 1974). Other space and ground-based observations of zodiacal light have also shown irregularities in the brightness distribution (Sparrow and Ney, 1972; Dumont and Sánchez, 1975). Despite these observational indications, structures in the zodiacal light have generally been ignored for two reasons. First, there was a lack of detailed information on the distribution of background starlight over the sky. Second, for ground observations it is difficult to determine the airglow continuum and to correct for airglow and astronomical diffuse background that is scattered into the telescope's field of view by the Earth's atmosphere.

Figure 1 shows Pioneer 10 near-Earth observations of zodiacal light brightness as a function of differential ecliptic longitude $\lambda-\lambda_\odot$ for various ecliptic latitudes. Connection of the points in Figure 1

*On leave of absence from Seoul National University, Korea.

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 33–37.

Planet. Space Sci., Vol. 33, No. 11, pp. 1359-1362, 1985
Printed in Great Britain

0032-0633/85 $3.00 + 0.00
Pergamon Press Ltd.

SHORT PAPER

THE SIZE OF THE GRAVITATIONAL ZONE OF INFLUENCE OF A PLANET ACTING ON THE ORBITAL ELEMENTS OF SMALL CELESTIAL BODIES

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(Received in final form 28 August 1985)

ABSTRACT

Tisserand's definition of the "sphere of action" of a planet is based on the equality of tidal vs. gravitational acceleration ratios of the sun and planet. Öpik and others based their relation on equating the differential solar and planetary forces on the particle. Neither expression was formulated to describe the zone of influence surrounding a planet when considering the small but significant (i.e. long-term) perturbative effects of the planets on a particle's orbital elements. For the purpose of determining these effects on interplanetary dust we dervive a zone of influence based on equating the gravitational forces of the sun and planet, and demonstrate its applicability by utilizing the particle's closest approach to the planet as a measure of the zone of influence.

INTRODUCTION

In the process of computing the orbital evolution of dust particles in interplanetary space, it was necessary to determine whether or not a particle was close enough to a planet that integrating the perturbing forces using Encke's method was no longer valid. Both expressions for the "sphere" of influence of a planet proved to be inadequate when the geometries of subsequent interactions were considered. In particular, when each relation was scaled to one planet, it could not be generalized to the other planets. Consequently, the formula for the zone of influence must depend strongly on the specific subject to be studied. We have studied this dependence using changes in several orbital elements as our criteria.

THEORY

The general expression for the radial distance to the boundary of the planetary zone of influence on small particles can be written as

$$s = k \cdot f(a_p) \cdot g(m_p, \text{ other planetary parameters}) \qquad (1)$$

where k is a constant which depends on the nature of the problem under study, f and g are functions, a_p is the planet's semimajor axis, and m_p is the planet's mass. The other parameters may include the eccentricity of the planet, as well as the other orbital parameters and such factors as oblateness and axial tilt. Functions f and g are generally not separable but we have found that the effect of semimajor axis can be separated from the other parameters. The equations of Tisserand (1889) and Öpik (1951) can be written as

$$s = (1/M_\odot)^{2/5} a_p m_p^{2/5}, \text{ and} \qquad (2)$$

$$s = \tfrac{1}{2}(\tfrac{1}{2}M_\odot)^{1/3} a_p m_p^{1/3}, \text{ respectively.} \qquad (3)$$

If we equate the gravitational and radiation forces of the sun and planet, a different relationship is obtained. Consider a particle of mass m at a distance s from a planet of mass

THE GRAVITATIONAL ZONES OF INFLUENCE OF THE PLANETS ACTING ON SMALL CELESTIAL BODIES

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ABSTRACT. Tisserand's definition of the "sphere of action" of a planet is based on the equality of tidal vs. gravitational acceleration ratios of the sun and planet. Öpik and others based their relation on equating the differential solar and planetary forces on a particle. Neither expression was formulated to describe the zone of influence surrounding a planet when considering the small, but significant, long-term perturbative effects of the planets on a particle's orbital elements. For the purpose of determining these effects on interplanetary dust we derive a zone of influence based on equating the gravitational forces of the sun and planet.

The general expression for the radial distance to the boundary of the planetary zone of influence on small particles can be written as

$$s = k \cdot f(a_p) \cdot g(m_p, \text{ other planetary parameters}) \qquad (1)$$

where k is a constant which depends on the nature of the problem under study, f and g are functions which may also have the same dependence as k, a_p is the planet's semimajor axis, and m_p is the planet's mass. The other parameters may include the eccentricity of the planet, as well as other orbital parameters and such factors as oblateness and axial tilt. Functions f and g are generally not separable but we have found that the effect of semimajor axis can be separated from the other parameters. The equation of Tisserand (1889) and Öpik (1951) can be written as

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If we equate the gravitational and radiation forces of the sun and planet, a different relationship is obtained. Consider a particle of mass m at a distance s from a planet of mass m_p and semimajor axis a_p, and at a distance r from the sun. The magnitude of the force on the particle due to the planet is

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GROUND-BASED OBSERVATIONS OF NEAR ECLIPTIC ZODIACAL LIGHT BRIGHTNESS

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ABSTRACT. Ground-based observations of the evening zodiacal light taken by Weinberg and Mann from Mt. Haleakala, Hawaii, during March 1966 are used to derive a table of zodiacal light brightnesses at high spatial resolution (as little as 0.5° in differential ecliptic longitude $\lambda-\lambda_\odot$ and 1.0° in ecliptic latitude β) over the region $29.5° < \lambda-\lambda_\odot < 56°$, $-30° < \beta < 30°$. Significant differences are found in the brightness distributions above a d below the ecliptic plane.

Brightness, polarization, color and angular dependence of the light of the night sky were systematically observed by Weinberg and Mann from Mt. Haleakala, Hawaii between 1965 and 1969 (Weinberg and Mann, 1967). One of the several observing techniques that was used involved scanning the main cone of the zodiacal light over a range of 160° in azimuth centered on the ecliptic, beginning (evening) or ending (morning) with the onset of astronomical twilight. A multicolor photopolarimeter scanned back and forth in azimuth at 2.5 deg/sec, incrementing elevation in 1° steps between 5° and 24°. A sample of these data, taken in March 1966 at 5080Å, is reduced to isolate the zodiacal light. Additional data and full details of the observations, calibration, and data reduction will be presented elsewhere.

Data below elevation 10° are omitted here due to difficulties in the atmospheric corrections. The measured brightnesses were converted to absolute units ($S_{10}(V)_{G2V}$) by reference to a calibrated (by NBS Fritz Peak Observatory), 17.8-cm diameter ^{14}C-activated phosphor source. The source was placed over the objective before and after each night's observations, filling both the aperture and the 3° diameter field of view (FOV). Bright stars were used to obtain an independent absolute calibration, the two methods agreeing to better than 5 percent.

Extinction corrections were made with coefficients derived from observations of bright stars using the same instrument. Atmospheric scattering corrections followed the method outlined by Weinberg (1964). The brightness contributed by "resolved" stars in each FOV were subtracted using a special merged star catalog developed for each color used with this instrument. Background starlight was subtracted using data obtained from Pioneer 10 observations beyond the asteroid belt, where the zodi-

R. H. Giese and P. Lamy (eds.), Properties and Interactions of Interplanetary Dust, 11–15.

THE CHANGE IN NEAR-ECLIPTIC ZODIACAL LIGHT BRIGHTNESS WITH HELIOCENTRIC DISTANCE

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ABSTRACT. Background starlight observed by the Pioneer 10 Imaging Photopolarimeter from beyond the asteroid belt is used to isolate zodiacal light in Pioneer observations at heliocentric distances R between 1 and 3 AU. Near-ecliptic zodiacal light brightness data in the range 65° to 180° elongation ε are used to depict changes in the shape of the zodiacal light with ε and R and are compared to the corresponding views seen from the Earth and from the Helios 1 and 2 spacecraft.

The heliocentric dependence of zodiacal light can only be observed directly by a space probe, the first such probe measurement being made by Pioneer 10. During the cruise phase of this outer solar system mission, sky brightness and polarization were mapped using a photopolarimeter (Weinberg, et al.; 1973, 1974). At elongations greater than 90°, the contribution of zodiacal light decreased to negligible levels beyond 3 AU (Hanner, et al.; 1974, 1976). As part of an analysis of additional Pioneer 10 data, Schuerman, et al. (1977) pointed out that there is no evidence for the zodiacal light being absent beyond 3 AU - only that it becomes vanishingly small compared to the background starlight (integrated starlight, diffuse galactic light, extragalactic background light). These studies are extended to smaller elongations and, for the first time, zodiacal light brightnesses are tabulated as a function of ε, β, and R (Table 1).

Since zodiacal light is negligible at large R, observations in these regions have been used to derive maps of background starlight over the sky (Toller, 1981; Weinberg, 1981). These data and brightnesses due to discrete ($m_V < 6.5$) stars are subtracted from Pioneer 10 observations between 1 and 3 AU to derive the 4400Å ε,β,R zodiacal light topology given in Table 1. The three entries in each ε,R box correspond to data at ecliptic latitudes β = +10°, 0°, -10° from top to bottom, respectively. Empty boxes indicate regions not yet analyzed. Blank areas within a box denote regions where the data was either not analyzed or is uncertain due to the presence of a bright star in the field of view. Additional Pioneer 10 blue data and the corresponding Pioneer 10 red (6400Å) data will be similarly analyzed and published elsewhere.

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ZODIACAL LIGHT AND INTERPLANETARY DUST

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ABSTRACT. Recent results on zodiacal light are used to show that optics, dynamics, and infrared must be considered *together* to properly and fully characterize the interplanetary dust complex.

Zodiacal light observations have been widely used to infer the large scale properties of the interplanetary dust - with mixed results. Zodiacal light is certainly more stable (and better understood) than the published literature would suggest over the 25 years that it has been studied by this writer. The interested reader can trace this history in the Proceedings of this Colloquium's predecessor meetings (Honolulu 1967, Heidelberg 1975, Ottawa 1979), in triennial Reports on Astronomy of IAU Commission 21, and in various reviews (e.g.: Leinert 1975; Weinberg and Sparrow 1978; Fechtig, Leinert, and Grün 1981).'

There have been intensive ground and space observations over the past two decades together with laboratory and theoretical studies, and, as we entered the 1980's, there was general agreement that:

- zodiacal light has solar color from the near UV to the near IR, except for a slight reddening in sky regions observed near the sun
- zodiacal light brightness is relatively smooth and remarkably stable over times as long as a solar cycle (Burnett 1976; Dumont and Levasseur-Regourd 1978; Leinert, et al. 1982a)
- zodiacal light brightness decreases monotonically with heliocentric distance R and is negligible beyond the asteroid belt (Hanner, et al.; 1974, 1976)
- zodiacal light is partially plane polarized with its electric vector perpendicular to the scattering plane, except for regions at large elongations where there is polarization reversal (electric vector parallel to scattering plane).

Recent results present a somewhat different, more complex picture of the interplanetary dust. Representative of this changing "view" are the recent, exciting observations by IRAS. Figure 1 shows IRAS 4-color data on total thermal emission for representative ecliptic pole-to-pole scans. The zodiacal emission peaks near the ecliptic, is the dominant source at 12, 25, and 60μm, and appears to be the brightest diffuse

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